Exploring Extremely Dense Medim in Heavy-Ion Collisions

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Relativistic Heavy-Ion Collisions

**Physics**
- Hot & dense medium
- Early Universe
- Quark-gluon plasma
- QCD phase structure

- QGP Formation
- Strongly coupled QGP

**LHC (2010~)**
- Precision measurement of the QGP
Brief History of Relativistic HIC

- **AGS** -1996
- **SPS** 1994-2000
- **RHIC** 2000-
- **LHC** 2010-

10GeV | $10^2$GeV | 1TeV | $\sqrt{s_{NN}}$

High Energy Frontier

Picture of fireball by Soushi Nonaka
Interaction rate
- FAIR, J-PARC-HI: $\sim 10^7$ Hz
- AGS, SPS: $\sim 10^2$ Hz
2 Main Goals

Exploring Dense Medium
- QCD phase diagram
- 1\textsuperscript{st} order phase transition
- equation of state

Rare-event Factory
- hyper nuclei
- exotic hadrons
- hadron interaction
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QCD Phase Diagram

- Gluon Plasma
- QCD Critical Point
- Hadronic Phase
- Color

Early Universe

Temperature $T_c$

Baryon chemical potential $\mu_c$

Compact Stars
Baryon Stopping
Baryon Stopping

High energy
Nuclear transparency
net-baryon #: small

Low energy
Baryon stopping
net-baryon #: large
Beam-Energy Scan

$T, \mu$ from particle yield

Translation to baryon density

Highest baryon density

$$\sqrt{s_{NN}} = 3 \sim 8\text{GeV} \quad (E_{\text{lab.}} = 15 \sim 100\text{AGeV})$$
Maximum Density

Time evolution in $T$-$\rho$ plane by JAM

- $\sqrt{s_{NN}} > 100 \text{ GeV}$
- $\sqrt{s_{NN}} \simeq 6 \text{ GeV}$
- $E/A = 20 \text{ GeV}$
- $E/A < 1 \text{ GeV}$

- Maximum density $5\sim10\rho_0$ @ $E/A\sim20\text{GeV}$
- Large event-by-event fluctuations?

A. Ohnishi, 2002
Beam-Energy Scan

Temperature

$T_c$

Baryon chemical potential

$\mu_c$
Event-by-Event Fluctuations

Review: Asakawa, MK, PPNP 90 (2016)

STAR, PRL 105 (2010)

Cumulants

\[ \langle \delta N_p^2 \rangle, \langle \delta N_p^3 \rangle, \langle \delta N_p^4 \rangle_c \]
Non-Gaussian Cumulants

Gaussian fluctuations diverge at the QCD-CP

- Higher order cumulants change sign at the phase boundary

$$\langle \delta N^3 \rangle = T \frac{\partial \langle \delta N^2 \rangle}{\partial \mu}$$

Asakawa, Ejiri, MK, 2009

- Steeper divergence for higher-order cumulants

Stephanov, 2009
Experimental Results

Enhancement & Suppression
of non-Gaussian cumulants!

Have we observed QCD critical point?

STAR Collab.
2010~
Non-Gaussian Cumulants have been observed as a function of rapidity window $\Delta y$.
Some results have non-monotonic $\Delta y$ dependence.
We want to see fluctuations around phase transition. But, fluctuations are modified due to diffusion before observation.
Rapidity Window dependence as a Result of Diffusion

- Higher order cumulants can behave non-monotonically.
- $\Delta \eta$ dependence encodes history of time evolution.

Parameters

\[
D_4 = \frac{\langle Q_{(net)}^4 \rangle_c}{\langle Q_{(tot)} \rangle} = 4
\]
\[
D_2 = \frac{\langle Q_{(net)}^2 \rangle_c}{\langle Q_{(tot)} \rangle} = 1
\]
\[
b = \frac{\langle Q_{(net)}^2 Q_{(tot)} \rangle_c}{\langle Q_{(net)} \rangle}
\]
\[
c = \frac{\langle Q_{(tot)}^2 \rangle_c}{\langle Q_{(tot)} \rangle}
\]

$\Delta \eta \approx 1.0$ (rough estimate)
Rapidity Window dependence as a Result of Diffusion

Higher order cumulants can behave non-monotonically.

Δη dependence encodes history of time evolution.
Various Observables

- Flow
- Dilepton / photon
- Fluctuations, higher-order cumulants
- $\Xi$, $\Omega$, ...

- Sophisticated event selections
- Various correlations

Can we select these events??
MK, Sakaguchi, Sako, Nara, Ohnishi, ...
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- hyper nuclei
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Search of Rare Events

- Exotic Hadrons
- Hypernuclei
- Strangelets
- hadron Interaction

Rare-event Factory

- High density
- High luminosity
- High strange yield

- creation
- properties
- interaction
Theoretical Challenges

RHIC / LHC
- creation of QGP
- hydro. models
- early thermalization
- (boost invariance)
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**RHIC / LHC**
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**Low-E Collisions**
- Initial condition?
- Threshold of QGP formation
- “Integrated” approach
  - Hydro x Cascade

J-PARC: Cascade  Hydrodynamics
Hydro+JAM Integrated Model

Hydro+Hadron simultaneous time evolution
- Dense hadrons → Hydronize
- Cooled hydro → Hadronize

Particle ratio is well described!

Akamatsu, ..., Nara, et al. PRC98 (2018)
Murase, Tuesday F-2
Exploring dense medium in relativistic heavy-ion collisions is one of the hottest topics in this field. Many new experiments will start in the near future!

Fluctuations are promising observables for the search for the phase structure of QCD.

Studies of hypernuclei and exotic hadrons are other important subjects in the future heavy-ion experiments.
J-PARC Heavy-Ion Program

H. Sako, this afternoon (E-3)

- New HI Injector
  - High intensity
  - Reliable / high-performance RCS & main ring
  - Reduce cost and time

- Beam energy: ~19 GeV/A
- Fixed target exp.
- Collision rate ~10^8 Hz
- Launch: 2025~?

http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/
Negatively-charged hypernuclei ($\Xi^-\text{n, }\Xi^-\text{nn, ...}$)
- Nuclear strangelets
- n-rich / p-rich hypernuclei

Measurement of magnetic moments
Hadron-hadron Interaction

ΛΛ Correlation function

Hadron interaction can be studied from correlation function.

Morita, Furumoto, Ohnishi, 2015
Radial Flow $dv_1/d\eta$

1. $dv_1/d\eta > 0$
2. $dv_1/d\eta < 0$
Directed Flow: $\frac{dv_1}{d\eta}$

- $dv_1/dy$: two sign change
- No transport models can reproduce it quantitatively
$d\nu_1/dy$: Signal of 1st Phase Tr.?

Negative $\nu_1$

$\approx 1^{st}$ order transition??

Nara+, 2017
Large event-by-event fluctuations even with fixed centrality.

“Maximum density” dependence may be studied experimentally.

average transverse energy

non-monotonic behavior as evidence of 1st. tr?
Lepton & Photon: Hierarchical Observation

Time scale: $10^{-1}$s

gravitational wave

photons

EM probes

hadronic observables

Time scale: $10^{-22}$s

di-lepton yield
Particle yields having strangeness have maximum at J-PARC energy
Exotic Hadrons

Hypernuclei

Strangelets

Exotic Hadrons

hadron Interaction